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Compensating deviations during flexible pin-type moulding of spatially curved CFRP by using 3D-surface detection

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Abstract

Laminating carbon-fiber-reinforced plastic (CFRP) traditionally uses rigid moulds. This process means that customising CFRP components is expensive since the costs of each rigid mould are allocated fully to only one associated CFRP. Therefore, using form-flexible moulds is beneficial, because it would eliminate the conventional restriction that each CFRP geometry needs one single rigid mould. The costs of one flexible mould would be allocated to all produced CFRP components. Thus, the more CFRP laminated on this single form-flexible mould, the less the CFRP is affected by mould costs. Creating form-flexible moulds by using pin-type tooling results in a discrete pin accumulation. To achieve the required continuous laminating surface, an interpolation layer is placed on the pins. However, compared to conventional CFRP moulds, normally made by CNC-milling, pin-type tooling complicates accuracy achievement. This is due to the fact that the elastic, silicone-like interpolation layer as well as several tolerances or inaccuracies within the mould mechanics, as an assembly, accumulate into the range of millimeters. Instead of using more accurate pin-type moulds, which is associated with increasing costs, this paper introduces an approach to integrate 3D surface detection methods into the process of form-flexible moulding of spatially curved CFRP using pin-type tools, which maintains costs and increases accuracy. The developed control loop compensates deviations dynamically and results in accuracies in the same range as parts produced using CNC-milled rigid moulds.

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Keywords: Quality Assurance; Form Flexible Moulding; Pin-Type Tooling; CFRP; 3D Surface Detection.

1. Introduction

Laminating carbon-fiber-reinforced plastic (CFRP) traditionally uses rigid moulds. Thus, each CFRP-geometry requires a specific mould. Accordingly, customising CFRP components is expensive since the costs of each rigid mould are allocated fully to one specific CFRP [1]. Therefore, reconfigurable tooling, such as multipoint moulding, is worthwhile to investigate [2], because it would eliminate the conventional requirement of a rigid mould for each CFRP geometry [1]. The costs of one flexible mould can be allocated to all produced CFRP components which reduces mould costs per CFRP overall. Figure 1 illustrates a form-flexible mould for laminating CFRP. This mould is designed by array-arranging height adjustable pins.

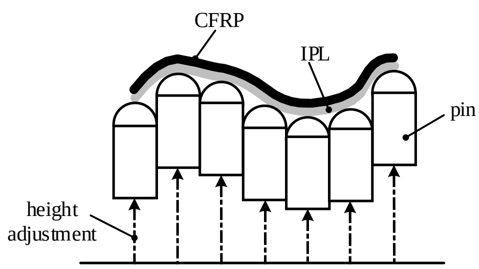

Fig. 1. Laminating CFRP using a form-flexible mould which is based on independently adjustable pins (pin-type moulding).

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Enabling form-flexible moulds by using pin-type tooling results in a discrete pin accumulation. To achieve the required continuous laminating surface, an interpolation layer (IPL) is attached to the pins. [3]

2. Need for action: using pin-type tooling for form-flexible moulding results in several inaccuracies which accumulate

Compared to conventional rigid CFRP-moulds, normally made by CNC-milling where no tolerance chain occurs due to being a single part, pin-type tooling complicates accuracy, as it is an assembly and tolerances must be added:

- The more pins are used within the multipoint mould, the more mechanical as well as control tolerances occur within the mould system. E.g., the following deviations $\delta_{vertical}$ accumulate in the vertical direction of a single pin's system $\delta_{vertical} = \delta_{spindle}$ (in the range of 1/10mm) + δ_{pin} (1/10mm) + δ_{IPL} (1/10mm) + $\delta_{control}$ (1/100mm) and the following deviations $\delta_{horizontal}$ accumulate in the horizontal direction by arranging pins $\delta_{horizontal} = \delta_{spindle\ position}$ (1/10mm) + $\delta_{pin\ position}$ (1/10mm) + $\delta_{assembly\ position}$ (1/10mm).
- Also, the elastic, silicone-like IPL shrinks (in the millimeter range) due to compressive stress as well as longitudinal tension. Thus, different stress conditions generated by different mould settings – due to mapping different geometries by different pin adjustments – lead to different height losses or increases specific to each pin. But, they cannot be compensated due to conservation of the volume and mass of the IPL.

Both types of inaccuracies accumulate over the entire mould system into the millimeter range, which is reflected in the final CFRP. As addressed in the following chapter, possibilities for decreasing these inaccuracies by modifying the mould design are limited.

3. Improving the mould design to increase accuracy is limited

Referring to the first reason, one possibility to increase the mechanical accuracy is to use manufacturing and assembly methods with higher precision. However, this increases the production costs of the mould. Also, it is possible to reduce the accumulation of inaccuracies by reducing the number of pins. But, this degrades the design freedom within the CFRP. This is due to the fact that decreasing the number of pins while maintaining the same moulding square results in larger pins which in turn cannot accommodate small geometry elements. This is illustrated by Fig. 2, where two pin-type moulds (three pins versus two pins) with the same moulding width a (and same depth b, which is not illustrated) are given. From a = 3 x (2 x R_1) = 2 x (2 x R_2) follows R_2 = 3/2 x R_1. Besides this, from l_2 = 2 x R_2 = 3 x R_1 and l_1 = 4 x R_1 it follows that l_2 = ¾ x l_1 and thus the laminating area decreases, in fact, and is not maintainable as constant.

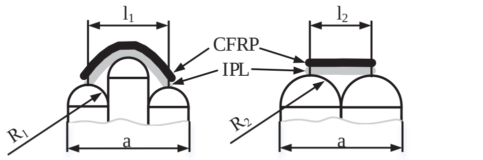

Fig. 2. Mould design with three vs. two pins while intending to maintain the same moulding size.

Referring to the second reason, the thicker the IPL, the lower the impact on shrinkage is for the same longitudinal stress. However, the flexibility of the IPL, and thus the ability to map filigree geometries in the CFRP, decreases as the IPL's thickness increases.

As addressed in the following chapter, a dynamic compensation enables the elimination of all the deviations δ (see section 2) and thus, results in more dimensionally stable final CFRP-parts, in the same accuracy range as parts produced by using CNC-milled rigid moulds.

4. 3D-scanning enables dynamic compensation of inaccuracies while not increasing the complexity of the present mould design

To circumvent the increased costs and requirements associated with using smaller pins in higher density to increase accuracy, this paper introduces an approach which integrates 3D surface detection methods into the process of height adjustment of the mould's pins, see Fig. 3.

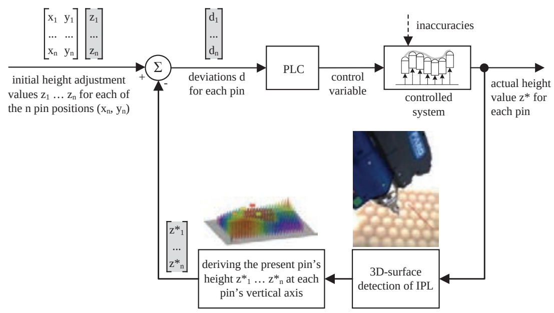

Fig. 3. Compensating inaccuracies within pin-type moulding: integrating 3D-surface detection into control loop for height adjustment of pins

In this process, the derived deviations are integrated into the control loop of the programmable logic controller (PLC), which permits the dynamic compensation of such deviations. The result is that the pin-type mould design does not have to be modified, which keeps mould costs minimal.

5. Method for integrating 3D surface detection into the mould's control loop to compensate inaccuracies

The overall method consists of following engineering packages or process flows, with the aim of achieving an adjusted pin-type mould wherein inaccuracies are compensated:

- initial height adjustment of mould pins (section 5.1),
- 3D-scanning of surface (section 5.2),
- deriving pin-specific deviations (section 5.3), and
- integrating 3D-surface detection into the control loop to compensate deviations dynamically (section 5.4).

These process steps are described in detail in the following sections.

5.1. Initial height adjustment of mould pins

As illustrated by Fig. 4, to adjust all of the mould pins, the CAD model of the CFRP and the mould's machine grid are superimposed. Then, the vertical movement of each pin is derived, which results in actuating the machine according to those values.

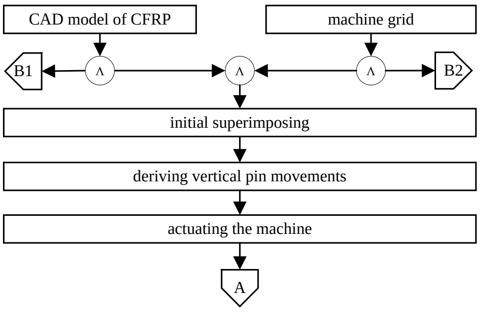

Fig. 4. Initial height adjustment of mould pins

Machine grid. The machine grid represents an ordered set of points. The (abstract) vertical main axis of a pin passes through each point. Fig. 5 illustrates an example of a pin-type mould consisting of 572 pins. The first point or pin axis in the example is at x = 0mm and y = 0mm.

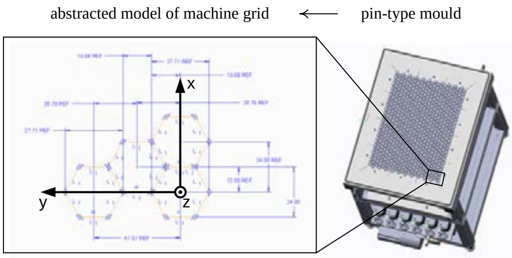

Fig. 5. Generating a machine grid of a pin-type mould with example pin positions.

CAD model of CRFP and initial superimposing. In the initial superimposing, the machine grid generated in the first step and the CAD model are superimposed, see Fig. 6.

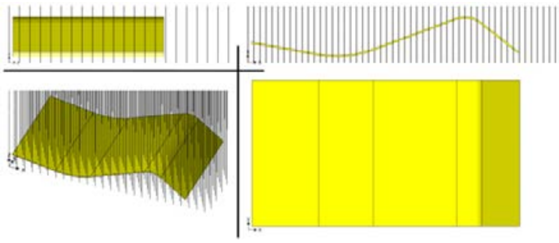

Fig. 6. Superimposing CFRP CAD model and machine grid.

Deriving vertical pin movements. The derivation is based on determining the points of intersection between the bottom surface of the CAD model and the pin axes. Consequently, only the pins being covered by the CFRP CAD model – as expressed by the green lines in Fig. 7 – are relevant and only they are assigned a height value. Finally, all pin height values are stored, e.g., in a text file [1].

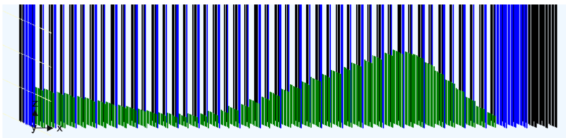

Fig. 7. Resulting pin height values (green lines).

Actuating the machine. Processing the height's actuation by sequential control of each pin allows the accessing of an external text file, which contains one height value for each pin. As expressed by Fig. 10, implementing p variables for p pins in the machine grid into the PLC-program allows the application of this same PLC-program to actuate p different pin heights. Thus, one text file is required for each CFRP-geometry, but the PLC-program does not need to be modified.

5.2. 3D-scanning of the surface

The 3D-scanning of the actual shape or surface is carried out after the initial height adjustment of pins (Fig. 8).

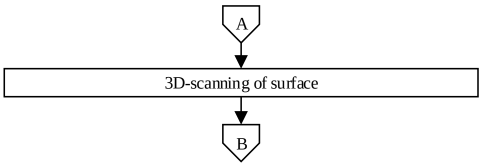

Fig. 8. 3D-scanning of the mould's actual surface after initial height adjustment but before deriving the pin-specific deviations

To detect the actual shape, optical measurement systems are well suited since they are contactless and available in different accuracies up to a few micrometers. The light section method, which is based on the principle of triangulation, is predominantly used for this purpose [4]. The two following methods are typically applied in commercial devices:

- Laser light method. A laser light is projected and reflected by the object as a deformed line, which is recorded by a camera. This camera is positioned relative to the object at a defined distance and angle. [5]
- Structured light method. A time-encoded binary pattern is projected on an object. The deformed lines are reflected and documented on a large area simultaneously by a camera. [6]

The laser light device requires moving the laser whereas the structured light device can remain stationary [7].

5.3. Deriving pin-specific deviations

Deriving the pin-specific deviations follows the 3D-scanning of the surface, which documents the actual mould geometry. It starts with a second superimposing that uses--in contrast to the first superimposing (see Fig. 4)--the 3D-scan of the actual surface, see Fig. 9.

Superimposing the 3D-scan, CAD model and machine grid. For a proper superimposing of the static items – the CAD model and the machine grid – it is mandatory that the model is generated within the same coordinate system as the machine grid (see Fig. 5). Furthermore a template is used that contains the coordinates of the measurement points.

In addition, the actual geometry of the adjusted pin-type mould from the 3D-surface detection must be registered to the target state. According to [8], among others, the following procedures can be used for registration:

- A registration using standard geometries (like cylinders, spheres or cones) is a very robust method, because it is less affected by noise errors than the single point method. Since the surfaces of the manufactured part are more or less free-form surfaces, the only way to use this method is the installation of standard geometries directly on the mould itself.
- As it is more flexible, a best-fit-registration is the most comfortable registration method. Within this iterative process, the distances between the corresponding areas are minimized using the least error square method. One disadvantage of this method is that it is probable that all pins will have to be re-controlled and not just some specific ones.

After superimposing, the subsequent process steps will derive p deviations for p pins and the resulting values will be saved in a text file for later integration into the PLC.

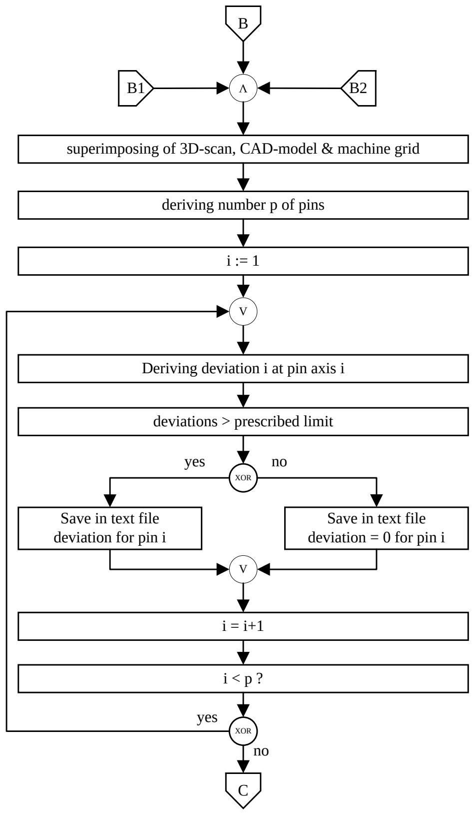

Fig. 9. Process flow for deriving pin-specific deviations

5.4. Integrating 3D-surface detection into control loop to compensate deviations dynamically

The integration of the 3D surface detection is based on the communication between the PLC and the text file wherein the pin-specific deviations are stored, see Fig. 10.

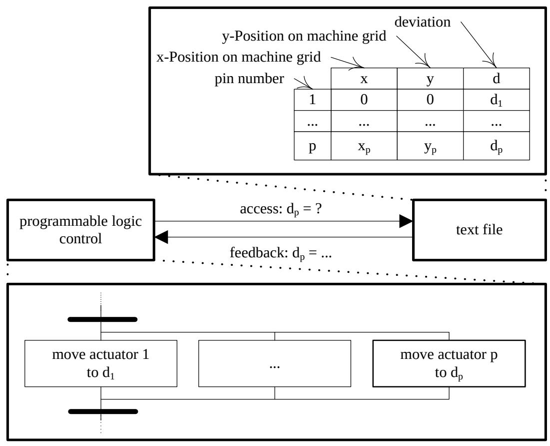

Fig. 10. Integrating text-file values z into sequential control of PLC

Each pin actuation value or variable within the PLC is assigned a line of text, including the pin's x- and y-coordinates and the corresponding value of deviation d_p. Once the step is reached within the sequential control, the PLC accesses the text file to return the corresponding pin's deviation value.

The overall process is illustrated by Fig. 11. Only those pins whose deviation exceeds the prescribed limit (compare with Fig. 9) are actuated, but the others (where $d_p = 0$) are not. In the present case it is assumed that each pin is individually accessible and thus can be individually controlled.

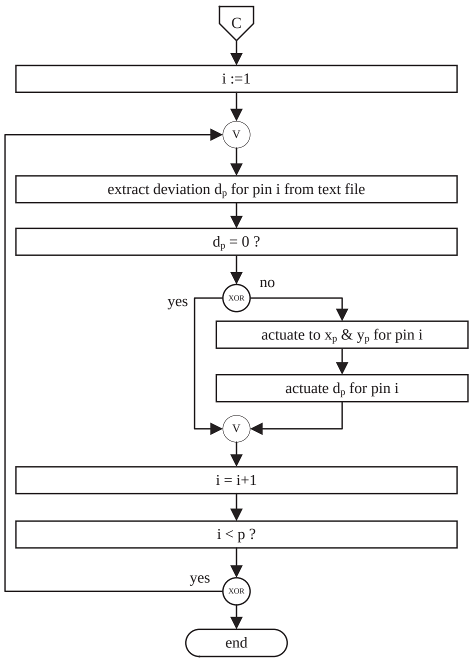

Fig. 11. Process flow to compensate the deviations

6. Case example

For a demonstration of the presented process, a case example is given in the following. A CFRP component with quantity one is used for a prototype model.

Starting with the CAD model, an initial adjustment of the machine grid is calculated by superimposing the ideal CAD model and the machine grid data. The determined values of the pins are transferred to the form-flexible mould and the initial position is configured.

The adjusted machine is measured afterwards using a structured light scanning device with an accuracy of about 1% of the measuring field size. For a first check of whether an update of the machine pin data is required, a false color print – using a best-fit-registration – of the deviations between the CAD model and digitalized mould can be displayed (Fig. 12).

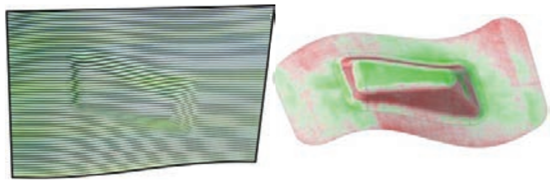

Fig. 12. Structured light pattern (left) and representation of the positive and negative deviations of the mould (right).

For a readjustment of the of the pin-type mould, every specific deviation of each pin must be separated. Therefore, a superimposing of the CAD model, the machine grid and the data from the scanning process is performed (Fig. 13).

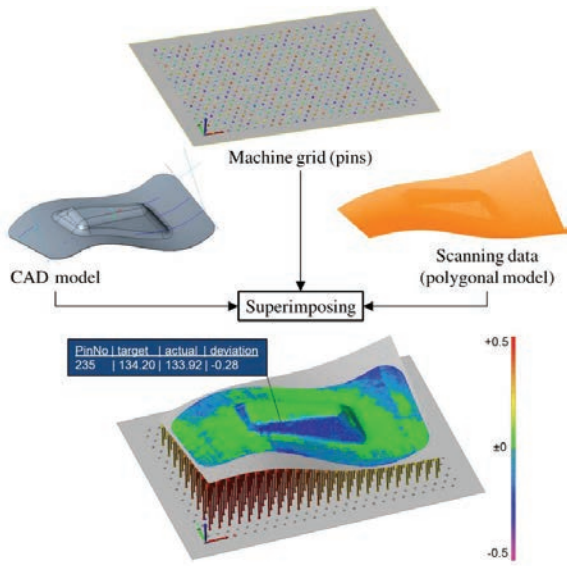

Fig. 13. Superimposing of CAD model, machine grid and scanned data.

With the results of the second superimposing process, a text file is created, containing all the deviations at each pin. Comparing the target and the actual values of the pin positions, a readjustment is performed at every pin with deviation not equal to zero (or within a given tolerance).

After this process, a machine with almost the exact shape is ready for the manufacturing of the CFRP component.

7. Summary, discussion and challenges for future work

Summary. As addressed within this contribution, improving the design of pin-type moulds for laminating CFRP by reducing the number of pins is limited since this degrades the design freedom within the CFRP. Furthermore, making the interpolation layer thicker reduces the impact of shrinkage due to longitudinal stress, but the flexibility of the IPL and thus the ability to map flexible geometries within the CFRP decreases at the same time. With a view to these limitations, this article contributes a method which integrates 3D surface detection into the mould's control loop to compensate deviations. The method requires no design modification of the existing pin-type mould, which means there are no increased mould costs.

The introduced overall process consists of four general packages which are: the initial height adjustment of mould pins, 3D-scanning of surface for documentation of the actual state, deriving the pin-specific deviations, and integrating 3D-surface detection into the control loop to compensate deviations dynamically.

Discussion. The compensation of deviations is limited by the measurement accuracy. Therefore a minimum requirement should be that the accuracy of the 3D-scanning is more accurate than the pin actuation accuracy.

Furthermore, it must be pointed out that flexible pin-type moulding requires a machine system with different mechatronic components. Thus, building up such a single system leads to significant higher initial costs compared to the classical milling of a single rigid mould from a block. Additionally, the approach introduced by this paper is based on 3D-surface detection which may also add extra costs. Those are in the range of hundreds to thousands of Euros, depending on the required measurement accuracy. At this point, the return on investment remains to be discussed. However, there is no universally verifiable statement in numerical terms possible, since the real costs can be only specified by case examples, as expressed by Fig. 14.

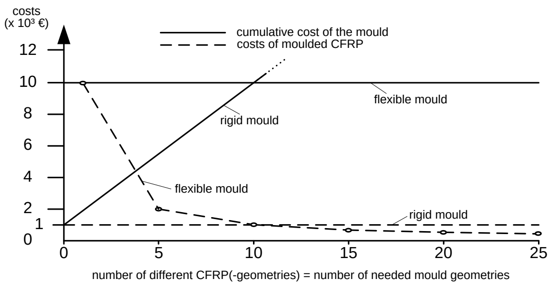

Fig. 14. Example for return on investment reached after a number of ten CFRPs with different geometries

Especially the needed mould's size affects the costs. But, a relative statement using variables is possible as addressed by Table 1. In the table, K represents the cost of acquisition of a single flexible pin-type mould, k represents the cost of acquisition of a single rigid mould (assuming that k < K) and x is the number of CFRP-parts with different geometries to be laminated. The return on investment is reached at K = x•k, which results in x = K/k as the necessary quantity to achieve the return on investment. In reality, there are also costs for storing or recycling rigid moulds, since they are not useful for new orders or CFRP-prototyping due to changes in geometry. Thus, k will be higher in real-life situations, resulting in a smaller required x to achieve the return on investment. But, at the same time, K will be larger due maintenance costs.

Table 1. Examples for necessary quantity to achieve the return on investment.

K in € / k in €	10,000	25,000	50,000	100,000
500	20	50	100	200
1,000	10	25	50	100
1,500	6.67	16.67	33.33	66.67
2,000	5	12.5	25	50

Concerning the time needed for adjusting one spatially curved moulding area by pin-type moulding, there are no qualitative disadvantages in time needed compared to the process of (CNC-)milling a rigid mould.

Challenges for future work. Regarding the communication between the PLC and the text file, which is illustrated in Fig. 11, it is not strictly necessary to access to the text file p times for each pin actuation but once, e.g., at the start of sequential control to map all corresponding deviation values at once to the actuation values d_n.

Furthermore, as stated in Fig. 11, the present work assumes that each pin is individually accessible. This sequential pin actuation method will lead to an increased time cost for the set-up of the entire pin-type mould as well as the time cost for the entire deviation compensation. As mentioned within [2], a (partially) simultaneous actuation of the pins can reduce its time cost.

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